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# Scaled momentum distributions for $K_S^0$ and $\Lambda/\bar{\Lambda}$ in DIS at HERA

ZEUS Collaboration

## Abstract

Scaled momentum distributions for the strange hadrons  $K_S^0$  and  $\Lambda/\bar{\Lambda}$  were measured in deep inelastic  $ep$  scattering with the ZEUS detector at HERA using an integrated luminosity of  $330 \text{ pb}^{-1}$ . The evolution of these distributions with the photon virtuality,  $Q^2$ , was studied in the kinematic region  $10 < Q^2 < 40000 \text{ GeV}^2$  and  $0.001 < x < 0.75$ , where  $x$  is the Bjorken scaling variable. Clear scaling violations are observed. Predictions based on different approaches to fragmentation were compared to the measurements. Leading-logarithm parton-shower Monte Carlo calculations interfaced to the Lund string fragmentation model describe the data reasonably well in the whole range measured. Next-to-leading-order QCD calculations based on fragmentation functions, FFs, extracted from  $e^+e^-$  data alone, fail to describe the measurements. The calculations based on FFs extracted from a global analysis including  $e^+e^-$ ,  $ep$  and  $pp$  data give an improved description. The measurements presented in this paper have the potential to further constrain the FFs of quarks, anti-quarks and gluons yielding  $K_S^0$  and  $\Lambda/\bar{\Lambda}$  strange hadrons.

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# 1 Introduction

The jet fragmentation and hadronisation processes through which coloured partons become bound in colour-neutral hadrons cannot be described within the framework of perturbative QCD (pQCD). Several approaches have been developed which attempt to build a bridge between the fixed-order partonic cross sections and the observed hadrons. Two of the most successful and widely used approaches are the Lund string model [1] and the fragmentation functions (FFs) [2–6]. The Lund string model, relying on a large number of parameters, is interfaced to leading-logarithm parton-shower Monte Carlo models. The FFs are parameterisations of the hadronisation process within the standard framework of leading-twist collinear QCD factorisation, in a similar way to that of the parton distribution functions (PDFs), and are convoluted with the predicted partonic cross sections.

Extensive studies of the fragmentation properties of the hadronic final state have been performed in  $e^+e^-$  [7–19],  $pp$  [20–23],  $p\bar{p}$  [24] and deep inelastic  $ep$  scattering<sup>1</sup> (DIS) [25–33] data and have provided information about the fragmentation and hadronisation processes. The measurements provided tests of pQCD and showed that scaling violations are observed. In addition, the comparison of the measurements in different reactions indicated an approximately universal behaviour of quark fragmentation.

In a previous publication [28], the ZEUS Collaboration presented high-precision measurements of inclusive charged-hadron production. Next-to-leading-order (NLO) QCD calculations, based on different FFs obtained from fits [34–36] to  $e^+e^-$  data, from fits [37] to  $e^+e^-$ ,  $pp$  and  $p\bar{p}$  data and from fits [38, 39] to  $e^+e^-$ ,  $pp$  and  $ep$  data, were compared to the measurements. The predictions based on the different FFs are similar and fail to provide a good description of the measurements over the full range of applicability of the calculations. The parameterisations [38, 40, 41] of the FFs for strange hadrons, such as  $K_S^0$  and  $\Lambda$ , are so far largely unconstrained. The  $ep$  data presented in this paper have the potential to constrain these FFs over a wide kinematic range.

In this paper, the scaled momentum distributions for  $K_S^0$  and  $\Lambda$  hadrons<sup>2</sup> are presented for the first time in DIS. The scaled momentum is defined as  $x_p = 2P^{\text{Breit}}/\sqrt{Q^2}$ , where  $P^{\text{Breit}}$  is the particle momentum in the Breit frame and  $Q^2$  is the photon virtuality. The Breit frame [42, 43] is the frame in which the exchanged virtual boson is purely space-like, with 3-momentum  $\mathbf{q} = (0, 0, -Q)$ , providing a maximal separation between the products of the beam fragmentation and the hard interaction. The measurements were performed in the current region of the Breit frame, which is equivalent to one hemisphere in  $e^+e^-$  annihilations, as functions of  $Q^2$  and  $x_p$ . Next-to-leading-order predictions, based on different FFs, and leading-logarithm parton-shower Monte Carlo calculations, interfaced with the Lund string fragmentation model, were compared to the measurements.

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<sup>1</sup> Here and in the following, the term “electron” and the symbol “ $e$ ” denote generically both the electron ( $e^-$ ) and the positron ( $e^+$ ), unless otherwise stated.

<sup>2</sup> Here and in the following, the notation  $\Lambda$  includes both the particle and its antiparticle unless otherwise stated.

## 2 Theoretical framework

In lowest-order QCD, three processes contribute to the DIS cross section, namely the Born ( $V^*q \rightarrow q$ , with  $V^* = \gamma^*, Z^*$ ), the boson-gluon-fusion ( $V^*g \rightarrow q\bar{q}$ ) and QCD-Compton-scattering ( $V^*q \rightarrow qg$ ) processes. The cross section for the production of an observed hadron,  $H$ , in the final state in DIS can be expressed in QCD, using the factorisation theorem, as

$$\sigma(ep \rightarrow e + H + X) = \sum_{j,j'=q,\bar{q},g} f_{j/p}(x, Q) \otimes \hat{\sigma}_{jj'}(x, Q, z) \otimes F_{H/j'}(z, Q),$$

where the sum runs over all possible initial (final)-state partons  $j$  ( $j'$ ),  $f_{j/p}$  are the proton PDFs, which give the probability of finding a parton  $j$  with momentum fraction  $x$  in the proton,  $\hat{\sigma}_{jj'}$  is the partonic cross section, which includes the matrix elements for the three processes mentioned above, and  $F_{H/j'}$  are the FFs, which give the probability that a hadron  $H$  with momentum fraction  $z$  originates from parton  $j'$ . The scaled momentum variable  $x_p$  is an estimator of  $z$ . As for the PDFs, the FFs include contributions from quark, anti-quark and gluon fragmentation. Absolute predictions for the FFs cannot be calculated; however, the dependence of the FFs on the scale  $Q$  is calculable in pQCD and governed by renormalisation group equations, similar as for the PDFs.

The range of applicability of the FFs is limited to medium to large values of  $z$ , since the assumption of massless hadrons leads to a strong singular behaviour for  $z \rightarrow 0$ . At small  $z$ , finite mass corrections are important. However, the inclusion of small- $z$  mass corrections is not compatible with the factorisation theorem and thus the FFs with mass corrections cannot be used with fixed-order calculations. A possible solution is to introduce *a posteriori* mass-correction factors to take this effect into account [37].

A large improvement in the precision of the ingredients of the calculations has been achieved in the last few years. Matrix elements up to NLO accuracy are available for many processes; for DIS, this corresponds to  $\mathcal{O}(\alpha_s^2)$ . Parton distribution functions have become increasingly more precise, largely due to the high-precision HERA data. On the other hand, FFs, though increasing in accuracy [34–41], still lack the precision of the proton PDFs.

The data most widely used to extract the FFs comes from  $e^+e^-$  annihilations into charged hadrons [7–19]. These data are very precise and the predicted cross sections do not depend on PDFs. However, they do not provide information on how to disentangle quark and anti-quark contributions to the FFs and the gluon fragmentation remains largely unconstrained. In addition, the  $e^+e^-$  data have poor statistics at large  $z$ , leading to large uncertainties in this region of phase space. Several parameterisations of the FFs exist [34–36].

In the last few years, new one-particle inclusive measurements coming from both  $pp$  collisions [20–23] and DIS [44] became available. The inclusion of these data in the extraction of the FFs yields a much more complete picture of the fragmentation process and provides a direct handle on quark, anti-quark and gluon contributions. A global QCD analysis of  $e^+e^-$ ,  $pp$  and DIS data is now available for several hadrons [38,39]. This global FF set agrees with the previous extractions,

based on  $e^+e^-$  data alone, in the regions of phase space which are also well constrained by  $e^+e^-$  data alone.

### 3 Experimental set-up

A detailed description of the ZEUS detector can be found elsewhere [45, 46]. A brief outline of the components most relevant for this analysis is given below.

Charged particles were tracked in the central tracking detector (CTD) [47–49], the microvertex detector (MVD) [50] and the straw tube tracker (STT) [51]. The CTD and MVD operated in a magnetic field of 1.43 T provided by a thin superconducting solenoid. The CTD consisted of 72 cylindrical drift-chamber layers, organised in nine superlayers covering the polar-angle<sup>3</sup> region  $15^\circ < \theta < 164^\circ$ .

The MVD silicon tracker consisted of a barrel (BMVD) and a forward (FMVD) section. The BMVD contained three layers and provided polar-angle coverage for tracks from  $30^\circ$  to  $150^\circ$ . The four-layer FMVD extended the polar-angle coverage in the forward region to  $7^\circ$ . After alignment, the single-hit resolution of the MVD was  $24 \mu\text{m}$ . The transverse distance of closest approach (DCA) to the nominal vertex in  $XY$  was measured to have a resolution, averaged over the azimuthal angle, of  $(46 \oplus 122/p_T) \mu\text{m}$ , with  $p_T$  in GeV. The STT covered the polar-angle region  $5^\circ < \theta < 25^\circ$ . For CTD-MVD tracks that pass through all nine CTD superlayers, the momentum resolution was  $\sigma(p_T)/p_T = 0.0029p_T \oplus 0.0081 \oplus 0.0012/p_T$ , with  $p_T$  in GeV.

The high-resolution uranium-scintillator calorimeter (CAL) [52–55] covered 99.7% of the total solid angle and consisted of three parts: the forward (FCAL), the barrel (BCAL) and the rear (RCAL) calorimeters. Each part was subdivided transversely into towers and longitudinally into one electromagnetic section (EMC) and either one (in RCAL) or two (in BCAL and FCAL) hadronic sections (HAC). The smallest subdivision of the calorimeter was called a cell. Under test-beam conditions, the CAL single-particle relative energy resolutions were  $\sigma(E)/E = 0.18/\sqrt{E}$  for electrons and  $\sigma(E)/E = 0.35/\sqrt{E}$  for hadrons, with  $E$  in GeV.

The energy of the scattered electron was corrected for energy loss in the material between the interaction point and the calorimeter using the small-angle rear tracking detector [56, 57] and the presampler [56, 58].

The luminosity was measured using the Bethe-Heitler reaction  $ep \rightarrow e\gamma p$  by the luminosity detector [59–61] which consisted of two independent systems. In the first system, the photons were detected by a lead-scintillator calorimeter placed in the HERA tunnel 107 m from the interaction point in the lepton-beam direction. The second system was a magnetic spectrom-

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<sup>3</sup> The ZEUS coordinate system is a right-handed Cartesian system, with the  $Z$  axis pointing in the proton beam direction, referred to as the “forward direction”, and the  $X$  axis pointing towards the centre of HERA. The coordinate origin is at the nominal interaction point.

eter arrangement [62], which measured electron-positron pairs from converted photons. The fractional uncertainty on the measured luminosity was 1.8%.

## 4 Event selection

The data used in this analysis were collected during the running period 2005–2007, when HERA operated with protons of energy  $E_p = 920$  GeV and electrons of energy  $E_e = 27.5$  GeV, and correspond to an integrated luminosity of  $330 \text{ pb}^{-1}$ . The criteria to select DIS events are described below.

A three-level trigger system [46, 63] was used to select events online. It relied on the presence of an energy deposition in the CAL compatible with that of a scattered electron. At the third level, an identified electron [64] with an energy larger than 4 GeV was required.

Offline, the kinematic variables  $Q^2$ , inelasticity,  $y$ , and the Bjorken scaling variable,  $x$ , as well as the boost vector to the Breit frame were reconstructed using the double-angle (DA) method [65], which uses the angles of the scattered electron and of the hadronic system.

Deep inelastic scattering events were selected by the following requirements:

- $E'_e > 10$  GeV, where  $E'_e$  is the scattered-electron energy; this ensures a reconstruction efficiency above 95% and a purity of the scattered electron of  $\approx 100\%$ ;
- $y_e \leq 0.95$ , where  $y_e$  is the inelasticity estimated from the energy and angle of the scattered electron; this excludes events with spurious electrons in the forward region, which are produced predominantly by photoproduction;
- $y_{\text{JB}} \geq 0.04$ , where  $y_{\text{JB}}$  is the inelasticity estimated using the Jacquet-Blondel method [66]; this rejects events for which the DA method gives a poor reconstruction;
- $35 < \delta < 60$  GeV, where  $\delta = \sum (E_i - P_{Z_i})$  and  $E_i$  is the energy of the  $i$ -th CAL cell,  $P_{Z_i}$  is the momentum along the  $Z$  axis and the sum runs over all CAL cells; this removes the phase space where photoproduction background and events with initial-state radiation are expected;
- $|Z_{\text{vtx}}| < 50$  cm, where  $Z_{\text{vtx}}$  is the  $Z$  component of the position of the primary vertex; this reduces background from events not originating from  $ep$  collisions;
- $|X| > 12$  and  $|Y| > 12$  cm, where  $X$  and  $Y$  are the impact positions of the scattered electron on the RCAL, to avoid the low-acceptance region adjacent to the rear beampipe;
- the analysis was restricted to events with  $10 < Q^2 < 40000 \text{ GeV}^2$  and  $0.001 < x < 0.75$ .

These requirements selected a sample of  $2.16 \cdot 10^7$  DIS data events.

## 5 $K_S^0$ and $\Lambda$ selection and reconstruction

The strange hadrons  $K_S^0$  and  $\Lambda$  were identified via the charged-decay channels,  $K_S^0 \rightarrow \pi^+\pi^-$  and  $\Lambda \rightarrow p\pi^-$  ( $\bar{\Lambda} \rightarrow \bar{p}\pi^+$ ). The candidates were reconstructed using two oppositely charged tracks associated with a displaced secondary vertex. In the case of the  $K_S^0$ , the mass of the pion was assigned to both tracks. For the  $\Lambda$ , the mass of the proton was assigned to the track with the largest momentum, whereas the mass of the pion was assigned to the other track, since the proton always has a larger momentum than the pion for  $\Lambda$  baryons with momentum larger than 0.3 GeV.

All tracks were required to be in the region of high CTD acceptance,  $|\eta^{\text{track}}| < 1.75$ , where  $\eta = -\ln(\tan \theta/2)$  is the pseudorapidity in the laboratory frame and  $\theta$  is the polar angle with respect to the proton beam direction. The tracks had to pass through at least three CTD superlayers and were required to have transverse momenta  $P_T^{\text{track}} > 150$  MeV.

The analysis was restricted to the current region of the Breit frame by boosting the tracks to this frame and requiring  $P_Z^{\text{Breit}} < 0$ , where  $P_Z^{\text{Breit}}$  is the longitudinal momentum of the track in the Breit frame. The combined four-vector momentum of the two tracks in the Breit frame,  $P^{\text{Breit}}$ , was used to reconstruct  $x_p$ .

Additional selection criteria, similar to those used in a previous analysis [67], were applied to the selected candidates to maximise the purity of the sample with a minimum loss of statistics. These requirements were:

- $dca < 2$  cm, where  $dca$  is the distance of closest approach of the two tracks forming the candidate;
- $\chi^2/dof < 5$  for the  $\chi^2$  of the secondary vertex fit;
- $M(e^+e^-) > 60$  MeV, to eliminate background from photon conversion;
- $M(p\pi) > 1121$  MeV ( $M(\pi^+\pi^-) < 475$  MeV), to eliminate  $\Lambda$  ( $K_S^0$ ) background from the  $K_S^0$  ( $\Lambda$ ) sample;
- $\theta_{2D} < 0.03$  rad, where  $\theta_{2D}$  is the collinearity angle in the  $XY$  plane between the  $K_S^0$  ( $\Lambda$ )-candidate momentum vector and the vector defined by the interaction point and the  $K_S^0$  ( $\Lambda$ ) decay vertex;
- $\theta_{3D} < 0.04$  rad, where  $\theta_{3D}$  is the collinearity angle between the  $K_S^0$  ( $\Lambda$ )-candidate three-momentum vector and the vector defined by the interaction point and the  $K_S^0$  ( $\Lambda$ ) decay vertex;
- $L_{XY} > 0.5$  (1) cm, where  $L_{XY}$  is the distance between the  $K_S^0$  ( $\Lambda$ )-candidate decay vertex and the primary vertex in the transverse plane;
- $P_T^{\text{PA}} > (<) 0.11$  GeV, where  $P_T^{\text{PA}}$  is the projection of the pion momentum onto a plane perpendicular to the  $K_S^0$  ( $\Lambda$ ) momentum direction (the Podolanski-Armenteros variable [68]).

Figures 1 and 2 show the  $dca$ ,  $\theta_{2D}$ ,  $\theta_{3D}$  and  $L_{XY}$  distributions for data and Monte Carlo (see Section 6) for  $K_S^0$  and  $\Lambda$  candidates, respectively. The description of the data by the Monte Carlo simulation is adequate.

Figure 3 shows the  $M(\pi^+\pi^-)$  and  $M(p\pi)$  distributions after these requirements. A small amount of background is observed. The fit shown in Fig. 3 is for illustration only. The number of  $K_S^0$  ( $\Lambda$ ) candidates in each bin of  $x_p$  and  $Q^2$  was estimated by counting the entries in the signal region, 472 – 522 (1107.0 – 1124.5) MeV, and subtracting the number of expected background entries. The latter was determined from a linear fit to the sideband regions 403 – 422 and 572 – 597 (1086.0 – 1098.2 and 1133.2 – 1144.4) MeV, also indicated in Fig. 3. There were 806 505 (165 875)  $K_S^0$  ( $\Lambda$ ) candidates in the data sample. In the current region of the Breit frame, there were 238 153  $K_S^0$  and 40 728  $\Lambda$  candidates. A Monte Carlo study showed that 6% of the selected  $\Lambda$  candidates come from higher-baryon decays.

## 6 Monte Carlo simulation

Samples of Monte Carlo (MC) events were produced to determine the response of the detector and to correct the data to the hadron level. The MC samples were also used to compute predictions to be compared to the measurements.

The generated events were passed through the GEANT 3.21-based [69] ZEUS detector- and trigger-simulation programs [46]. They were reconstructed and analysed by the same program chain as used for the data. Particles with lifetime longer than  $3 \cdot 10^{-11}$  s, such as  $K_S^0$  and  $\Lambda$ , were treated as stable at generator level and their decays were simulated by GEANT.

Neutral current DIS events were generated using the program LEPTO 6.5.1 [70]. Radiative effects were estimated using the HERACLES 4.6.6 [71, 72] program with the DJANGO 1.6 [73, 74] interface to LEPTO. HERACLES includes QED corrections for initial- and final-state radiation, vertex and propagator terms, and two-boson exchange. The QCD cascade was simulated using the colour-dipole model (CDM) [75–78], including the leading-order QCD diagrams as implemented in ARIADNE 4.12 [79, 80] and, alternatively, with the MEPS model of LEPTO. Fragmentation into hadrons was performed using the Lund string model [1], as implemented in JETSET 7.41 [81–84]. The default parameter setting from the DELPHI/EMC [19, 85] tune was used for the hadronisation. The CTEQ5D [86] proton PDFs were used for these simulations.

## 7 Corrections and systematic uncertainties

The measured scaled momentum distributions were corrected to the hadron level and to the QED Born level. The correction factors were calculated bin-by-bin using the MC samples described in Section 6. The correction factors take into account: (i) the event-selection efficiency for the cuts listed in Section 4, but for the  $Q^2$  and  $x$  requirements; (ii) the efficiency to identify the  $K_S^0$  and

$\Lambda$  decays, as specified in Section 5; (iii) the migrations between bins due to detector resolution, which affects in particular the transformation to the Breit frame; (iv) the relevant branching ratios; and (v) the extrapolation to the full phase space. The factors calculated in the measured  $(x_p, Q^2)$  bins varied from 0.05 (0.05) to 0.18 (0.11) for  $K_S^0$  ( $\Lambda$ ) candidates, and reached  $\approx 0.25$  for candidates with momentum in the range 1 – 1.5 GeV and  $-1 < \eta < 1$ ; the lowest values were found for high  $Q^2$  and  $x_p$  values. Bins with an acceptance smaller than 0.05 were not used in the analysis. The QED correction factors were computed using the Monte Carlo samples; they are below 5% for  $Q^2 < 100 \text{ GeV}^2$  and increase to a maximum of 20% at the highest values of  $Q^2$ .

The total systematic uncertainties on the scaled momentum distributions are larger than the statistical uncertainties in most bins. The statistical uncertainties themselves vary significantly over the kinematic range. For  $K_S^0$  ( $\Lambda$ ), they are at the 1 (4)% level at low  $Q^2$  and between 10 to 90% (20 to 70%) over the  $x_p$  range at large  $Q^2$ . Many of the systematic uncertainties were observed to scale with the statistical uncertainty. In the following list, typical values of the uncertainties on the scaled momentum distribution are given separately for  $K_S^0$  and  $\Lambda$ , either as percentages of the statistical uncertainty or as absolute values:

- imperfections in the simulation causing uncertainties on DIS event reconstruction and selection resulted in uncertainties of  $^{+40}_{-30}\%$  and  $^{+50}_{-40}\%$  of the statistical uncertainties. This was evaluated by modifying the selection cuts within the experimental resolutions. At low  $Q^2$ , the variation of the cut on  $y_{JB}$  from 0.04 to 0.07 resulted in large uncertainties exceeding these typical values;
- an uncertainty of  $-2\%$  in the overall tracking efficiency resulted in absolute uncertainties of  $+4\%$  and  $+4\%$ ;
- detector-alignment uncertainties affecting the calculation of the boost vector to the Breit frame resulted in uncertainties of  $^{+30}_{-25}\%$  and  $^{+20}_{-15}\%$  of the statistical uncertainties. This was evaluated by varying separately the simulated polar angle of the scattered electron and of the hadrons by  $\pm 2 \text{ mrad}$ ;
- uncertainties on the  $K_S^0$  and  $\Lambda$  selection efficiency resulted in uncertainties of  $^{+80}_{-60}\%$  and  $^{+60}_{-60}\%$  of the statistical uncertainties. This was evaluated by varying the cuts listed in Section 5: the dominant effects were due to modifications of the cuts on  $\theta_{2D}$  to 0.015 and 0.06 and  $\theta_{3D}$  to 0.02 and 0.08;
- assumptions concerning the details of the simulation of the hadronic final state resulted in absolute uncertainties of  $^{+4}_{-3}\%$  and  $^{+10}_{-15}\%$ . At large  $Q^2$ , these uncertainties were larger and exceeded  $^{+15}_{-80}\%$  and  $^{+50}_{-25}\%$ . This was estimated by using MEPS instead of CDM in the calculation of the correction factors;
- background-subtraction uncertainties resulted in absolute uncertainties of  $^{+2}_{-2}\%$  and  $^{+3}_{-4}\%$ . At large  $Q^2$ , the uncertainties exceeded these typical values and were as high as  $\pm 35\%$  for both



$K_S^0$  and  $\Lambda$ . This was evaluated by varying the size of the background window by  $\pm 40\%$  and changing the background fit function from first to second order.

The systematic uncertainties were added in quadrature for each bin. The total systematic uncertainty is dominated by the uncertainty in the simulation of the hadronic final state. At low  $Q^2$ , the overall tracking efficiency also contributes significantly. At high  $Q^2$ , the uncertainties related to the  $K_S^0$  and  $\Lambda$  selection are important.

## 8 NLO QCD calculations

Next-to-leading-order QCD calculations, which combine the full NLO matrix elements with the proton PDFs and FFs as explained in Section 2, were compared to the measurements. For the comparison, the observable  $x_p$  is assumed to be equal to the variable  $z$ . For each bin in  $x_p$  and  $Q^2$ , a prediction was derived by numerical integration over the multiplicities  $d^2m(H)/dzdQ^2$ , with  $m(H)$  the number of  $H$  per DIS event. Two sets of calculations based on different parameterisations of the FFs were used. The first set was obtained from fits to  $e^+e^-$  data and based on the program CYCLOPS [87], called “AKK+CYCLOPS” [36, 37]. The second set was obtained from a global fit to  $e^+e^-$ ,  $pp$  and  $ep$  data, called “DSS” [38]. It was used only for  $K_S^0$  predictions.

The AKK+CYCLOPS calculations were performed using  $Q$  as the factorisation and renormalisation scales; the number of active quark flavours was set to  $n_f = 5$ ; the proton PDFs were parameterised using the CTEQ6M sets [88] and  $\Lambda_{\text{QCD}}$  was set to 226 MeV. The calculations were done assuming massless particles. Hadron-mass effects [89] for  $K_S^0$  and  $\Lambda$  were included as correction factors [37]. The influence on the shapes of the calculated scaled momentum distributions due to the mass effects is expected at small values of  $x_p$  and  $Q^2$ , as explained in Section 2.

In the DSS calculations, the scaled momentum distributions were obtained by convoluting the NLO DSS set of FFs together with the MRST NLO [90] PDFs and appropriate NLO coefficient functions. For these calculations,  $K_S^0$ -mass corrections were not included. The predictions were computed as ratios for each bin, such that a later combination of bins is not possible [91].

The uncertainty from terms beyond NLO was estimated by varying the renormalisation scale by factors 0.5 and 2. The uncertainties from FFs could not be evaluated so far; it is to a certain extent represented by the differences in the predictions of AKK+CYCLOPS and DSS. In addition, it should be noted that the DSS FFs were extracted from data at low  $Q^2$  and that the fits are thus almost unconstrained at high  $Q^2$  [38].



## 9 Results

Scaled momentum distributions,  $(1/N)(n(H)/\Delta x_p)$ , with  $n(H)$  the number of  $H$  ( $K_S^0$  or  $\Lambda$ ),  $N$  the number of DIS events in a given  $Q^2$  bin and  $\Delta x_p$  the width of the  $x_p$  bin, were measured in the current region of the Breit frame. The distributions are presented as functions of  $Q^2$  and  $x_p$  in the kinematic region of  $10 < Q^2 < 40000 \text{ GeV}^2$  and  $0.001 < x < 0.75$ .

Figure 4 shows the scaled momentum distributions for  $K_S^0$  as functions of  $Q^2$  in different regions of  $x_p$ . The results are also presented in Table 1. The data show clear scaling violation. This behaviour is expected on the basis of the QCD description of the parton evolution with increasing  $Q$ : the phase space for soft gluon radiation increases, leading to a rise of the number of soft particles with small  $x_p$ .

The predictions from the CDM and MEPS models, based on leading-logarithmic matrix elements plus parton shower and the Lund fragmentation model, as described in Section 6, are compared to the measurements in Fig. 4. They describe the shapes of the distributions fairly well while overestimating the overall production of  $K_S^0$  by 10 to 20%.

The NLO QCD calculations, based on full NLO matrix elements and the fragmentation-function approach described in Sections 2 and 8, are also compared to the measurements in Fig. 4 for  $x_p > 0.1$ . For  $z < 0.1$ , the calculations become singular.

The AKK+CYCLOPS calculations, based on FFs extracted from  $e^+e^-$  data alone, fail to describe the measurements. These calculations predict a much too high  $K_S^0$  rate but for  $x_p > 0.6$ . These discrepancies might come from the fact that the FFs used in these predictions have a poorly constrained gluon contribution, which is dominant at low  $x_p$ .

The DSS calculations, based on FFs extracted from a global analysis, give a good description of the measurements for  $x_p > 0.3$  and  $10 < Q^2 < 40000 \text{ GeV}^2$ . The prediction for this region of phase space is mainly constrained by  $pp$  data, which sufficiently constrain the FFs at high  $x_p$ . At lower  $x_p$ , the DSS calculations fail to describe the data. This can be explained by the fact that the DSS fit in this region of phase space is mostly unconstrained by the available data. Thus, the measurements presented in this paper will help to improve significantly such global fits in this region of phase space.

Figure 5 and Table 2 show the scaled momentum distributions for  $K_S^0$  as functions of  $x_p$  in two regions of  $Q^2$ . The predictions of CDM and MEPS give a good description of the data. In both regions of  $Q^2$ , both NLO calculations predict too-steep spectra. At low  $Q^2$ , this effect is especially pronounced.

Figures 6 and 7 show the scaled momentum distributions for  $\Lambda$ . The results are also presented in Tables 3 and 4. Scaling violations are clearly observed. The predictions of CDM and MEPS give a reasonable description of the measurements, but overestimate the overall  $\Lambda$  rate by  $\approx 20\%$ . The AKK+CYCLOPS NLO calculations fail to describe the measurements. As seen in Fig. 7, the predicted spectra in  $x_p$  are, as in the case of  $K_S^0$ , significantly too steep.

ZEUS has previously published measurements of scaled momentum distributions for inclusive charged particles in DIS [28]. These measurements are dominated by the contribution from charged pions. Figure 8 shows the scaled momentum distributions presented in this paper together with those from the inclusive charged particles analysis in the kinematic region of  $0.1 < x_p < 0.4$  as functions of  $Q^2$ . For  $Q^2 > 100 \text{ GeV}^2$ , all distributions show a plateau. At lower  $Q^2$ , and especially at low  $x_p$ , sizeable mass effects are expected. This is clearly visible. For  $0.1 < x_p < 0.2$ , the value of  $(1/N)(n(H)/\Delta x_p)$  drops to 10 (20)% of its maximum value for  $\Lambda$  ( $K_S^0$ ), while for inclusive charged particles, the  $(1/N)(n(H)/\Delta x_p)$  value is still 40% of the plateau value at the lowest  $Q^2$  accessible.

## 10 Summary and conclusions

Scaled momentum distributions for  $K_S^0$  and  $\Lambda$  hadrons were measured for the first time in  $ep$  DIS. The distributions were measured in the  $Q^2$  range from 10 to 40000  $\text{GeV}^2$  and  $0.001 < x < 0.75$ . Scaling violations were clearly observed for both the  $K_S^0$  and  $\Lambda$  hadrons.

Next-to-leading-order QCD calculations, based on different parameterisations of the FFs, were compared to the measurements. The predictions based on FFs extracted from  $e^+e^-$  data alone fail to describe the measurements. Those predictions based on a global analysis which include  $e^+e^-$ ,  $pp$  and  $ep$  data give an improved description of the measurements. However, they predict a too high production rate of  $K_S^0$  and  $\Lambda$  hadrons at low  $x_p$  and  $Q^2$ . The measurements presented in this paper have the potential to constrain significantly the FFs for the strange hadrons  $K_S^0$  and  $\Lambda$ .

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$Q^2$ (GeV <sup>2</sup> )	$0.0 < x_p < 0.1$	$0.1 < x_p < 0.2$	$0.2 < x_p < 0.3$
10 - 40	$0.031 \pm 0.001^{+0.002}_{-0.001}$	$0.125 \pm 0.001^{+0.008}_{-0.003}$	$0.144 \pm 0.001^{+0.009}_{-0.013}$
40 - 160	$0.171 \pm 0.002^{+0.009}_{-0.006}$	$0.392 \pm 0.003^{+0.018}_{-0.010}$	$0.283 \pm 0.002^{+0.013}_{-0.006}$
160 - 640	$0.551 \pm 0.010^{+0.025}_{-0.018}$	$0.612 \pm 0.010^{+0.028}_{-0.017}$	$0.306 \pm 0.007^{+0.014}_{-0.009}$
640 - 2560	$1.141 \pm 0.038^{+0.087}_{-0.037}$	$0.618 \pm 0.030^{+0.1130}_{-0.016}$	$0.309 \pm 0.029^{+0.047}_{-0.011}$
2560 - 10240	$1.878 \pm 0.168^{+0.095}_{-0.147}$	$0.834 \pm 0.217^{+0.065}_{-0.278}$	$0.115 \pm 0.062^{+0.066}_{-0.054}$
$Q^2$ (GeV <sup>2</sup> )	$0.3 < x_p < 0.4$	$0.4 < x_p < 0.6$	$0.6 < x_p < 1.0$
10 - 40	$0.1112 \pm 0.0008^{+0.0074}_{-0.0130}$	$0.0130 \pm 0.0004^{+0.0041}_{-0.0013}$	$0.0132 \pm 0.0001^{+0.0007}_{-0.0004}$
40 - 160	$0.1571 \pm 0.0019^{+0.0082}_{-0.0033}$	$0.0671 \pm 0.0009^{+0.0038}_{-0.0014}$	$0.0109 \pm 0.0003^{+0.0006}_{-0.0002}$
160 - 640	$0.1585 \pm 0.0060^{+0.0118}_{-0.0051}$	$0.0548 \pm 0.0027^{+0.0050}_{-0.0014}$	$0.0073 \pm 0.0008^{+0.0005}_{-0.0011}$
640 - 2560	$0.1053 \pm 0.0217^{+0.0319}_{-0.0214}$	$0.0558 \pm 0.0141^{+0.0176}_{-0.0028}$	$0.0029 \pm 0.0022^{+0.0014}_{-0.0030}$

**Table 1:** The measured scaled momentum distributions  $(1/N)(n(K_S^0)/\Delta x_p)$  as functions of  $Q^2$  in different regions of  $x_p$ . The statistical and systematic uncertainties are also shown.

$x_p$	$10 < Q^2 < 100 \text{ GeV}^2$	$100 < Q^2 < 40000 \text{ GeV}^2$
0.0 - 0.1	$0.0488 \pm 0.0006^{+0.0024}_{-0.0012}$	$0.4841 \pm 0.0063^{+0.0233}_{-0.0117}$
0.1 - 0.2	$0.1618 \pm 0.0009^{+0.0094}_{-0.0041}$	$0.5740 \pm 0.0061^{+0.0263}_{-0.0132}$
0.2 - 0.3	$0.1648 \pm 0.0009^{+0.0098}_{-0.0035}$	$0.3140 \pm 0.0048^{+0.0142}_{-0.0082}$
0.3 - 0.4	$0.1183 \pm 0.0007^{+0.0077}_{-0.0026}$	$0.1588 \pm 0.0037^{+0.01213}_{-0.0045}$
0.4 - 0.5	$0.0751 \pm 0.0006^{+0.0055}_{-0.0015}$	$0.0760 \pm 0.0027^{+0.0073}_{-0.0017}$
0.5 - 0.6	$0.0452 \pm 0.0004^{+0.0031}_{-0.0010}$	$0.0408 \pm 0.0022^{+0.0037}_{-0.0011}$
0.6 - 0.7	$0.0260 \pm 0.0003^{+0.0017}_{-0.0006}$	$0.0182 \pm 0.0015^{+0.0011}_{-0.0009}$
0.7 - 0.8	$0.0150 \pm 0.0002^{+0.0009}_{-0.0003}$	$0.0101 \pm 0.0012^{+0.0008}_{-0.0016}$
0.8 - 0.9	$0.0073 \pm 0.0001^{+0.0005}_{-0.0003}$	$0.0034 \pm 0.0007^{+0.0007}_{-0.0001}$
0.9 - 1.0	$0.0032 \pm 0.0001^{+0.0002}_{-0.0006}$	$0.0020 \pm 0.0006^{+0.0008}_{-0.0001}$

**Table 2:** The measured scaled momentum distributions  $(1/N)(n(K_S^0)/\Delta x_p)$  as functions of  $x_p$  in different regions of  $Q^2$ . Other details as in the caption to Table 1.



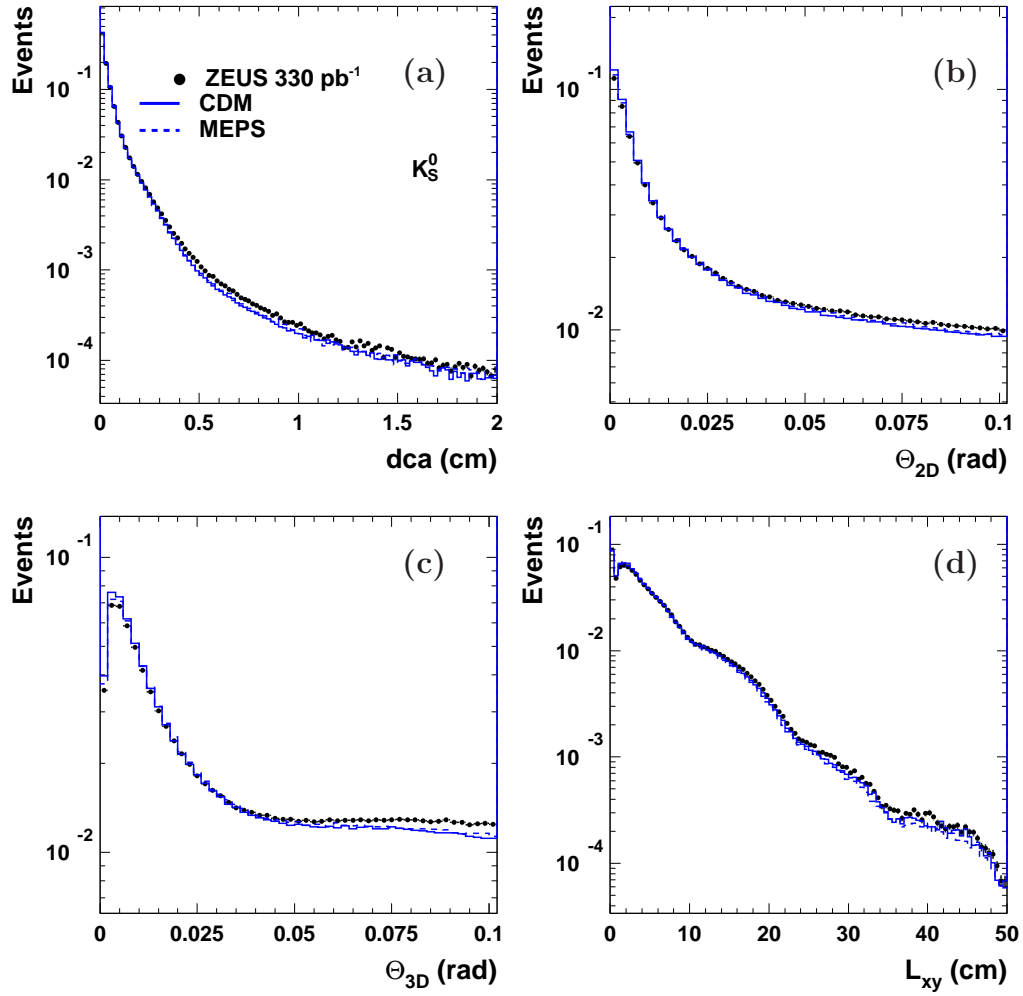
$Q^2$ (GeV <sup>2</sup> )	$0.0 < x_p < 0.1$	$0.1 < x_p < 0.2$	$0.2 < x_p < 0.3$
10 - 40	$0.0025 \pm 0.0002^{+0.0003}_{-0.0002}$	$0.0122 \pm 0.0004^{+0.0010}_{-0.0008}$	$0.0189 \pm 0.0005^{+0.0015}_{-0.0014}$
40 - 160	$0.0189 \pm 0.0014^{+0.0012}_{-0.0007}$	$0.0650 \pm 0.0021^{+0.0030}_{-0.0039}$	$0.0656 \pm 0.0018^{+0.0037}_{-0.0036}$
160 - 640	$0.0995 \pm 0.0095^{+0.0085}_{-0.0073}$	$0.1666 \pm 0.0099^{+0.0091}_{-0.0163}$	$0.0960 \pm 0.0066^{+0.0074}_{-0.0038}$
640 - 2560	$0.2313 \pm 0.0427^{+0.0593}_{-0.0567}$	$0.1966 \pm 0.0414^{+0.0124}_{-0.0303}$	$0.1038 \pm 0.0346^{+0.0132}_{-0.0090}$
2560 - 10240	$0.7416 \pm 0.4386^{+0.0577}_{-0.3574}$	$0.1962 \pm 0.1268^{+0.0393}_{-0.1395}$	
$Q^2$ (GeV <sup>2</sup> )	$0.3 < x_p < 0.4$	$0.4 < x_p < 0.6$	$0.6 < x_p < 1.0$
10 - 40	$0.0184 \pm 0.0004^{+0.0011}_{-0.0013}$	$0.0106 \pm 0.0002^{+0.0006}_{-0.0004}$	$0.0021 \pm 0.0001^{+0.0001}_{-0.0001}$
40 - 160	$0.0453 \pm 0.0015^{+0.0028}_{-0.0031}$	$0.0198 \pm 0.0007^{+0.0011}_{-0.0010}$	$0.0020 \pm 0.0002^{+0.0003}_{-0.0001}$
160 - 640	$0.0641 \pm 0.0074^{+0.0034}_{-0.0149}$	$0.0139 \pm 0.0025^{+0.0089}_{-0.0031}$	$0.0041 \pm 0.0009^{+0.0003}_{-0.0008}$
640 - 2560	$0.0653 \pm 0.0436^{+0.0119}_{-0.0244}$		

**Table 3:** The measured scaled momentum distributions  $(1/N)(n(\Lambda)/\Delta x_p)$  as functions of  $Q^2$  in different regions of  $x_p$ . Other details as in the caption to Table. 1.

$x_p$	$10 < Q^2 < 100 \text{ GeV}^2$	$100 < Q^2 < 40000 \text{ GeV}^2$
0.0 - 0.1	$0.00437 \pm 0.00034^{+0.00046}_{-0.00017}$	$0.08307 \pm 0.00638^{+0.00626}_{-0.00826}$
0.1 - 0.2	$0.01822 \pm 0.00059^{+0.00106}_{-0.00109}$	$0.13904 \pm 0.00466^{+0.00677}_{-0.01515}$
0.2 - 0.3	$0.02456 \pm 0.00059^{+0.00163}_{-0.00118}$	$0.09489 \pm 0.00275^{+0.00541}_{-0.00646}$
0.3 - 0.4	$0.02173 \pm 0.00049^{+0.00109}_{-0.00138}$	$0.056013 \pm 0.00188^{+0.00323}_{-0.00353}$
0.4 - 0.5	$0.01387 \pm 0.00035^{+0.00088}_{-0.00030}$	$0.02950 \pm 0.00135^{+0.00181}_{-0.00310}$
0.5 - 0.6	$0.00913 \pm 0.00026^{+0.00054}_{-0.00043}$	$0.014640 \pm 0.00095^{+0.00091}_{-0.00048}$
0.6 - 0.7	$0.00483 \pm 0.00018^{+0.00028}_{-0.00027}$	$0.00534 \pm 0.00051^{+0.00068}_{-0.00034}$
0.7 - 0.8	$0.00245 \pm 0.00011^{+0.00015}_{-0.00024}$	$0.00178 \pm 0.00028^{+0.00032}_{-0.00049}$
0.8 - 0.9	$0.00096 \pm 0.00006^{+0.0011}_{-0.00009}$	$0.00056 \pm 0.00019^{+0.00006}_{-0.00018}$
0.9 - 1.0	$0.00038 \pm 0.00004^{+0.00003}_{-0.00013}$	$0.00032 \pm 0.00013^{+0.00009}_{-0.00023}$

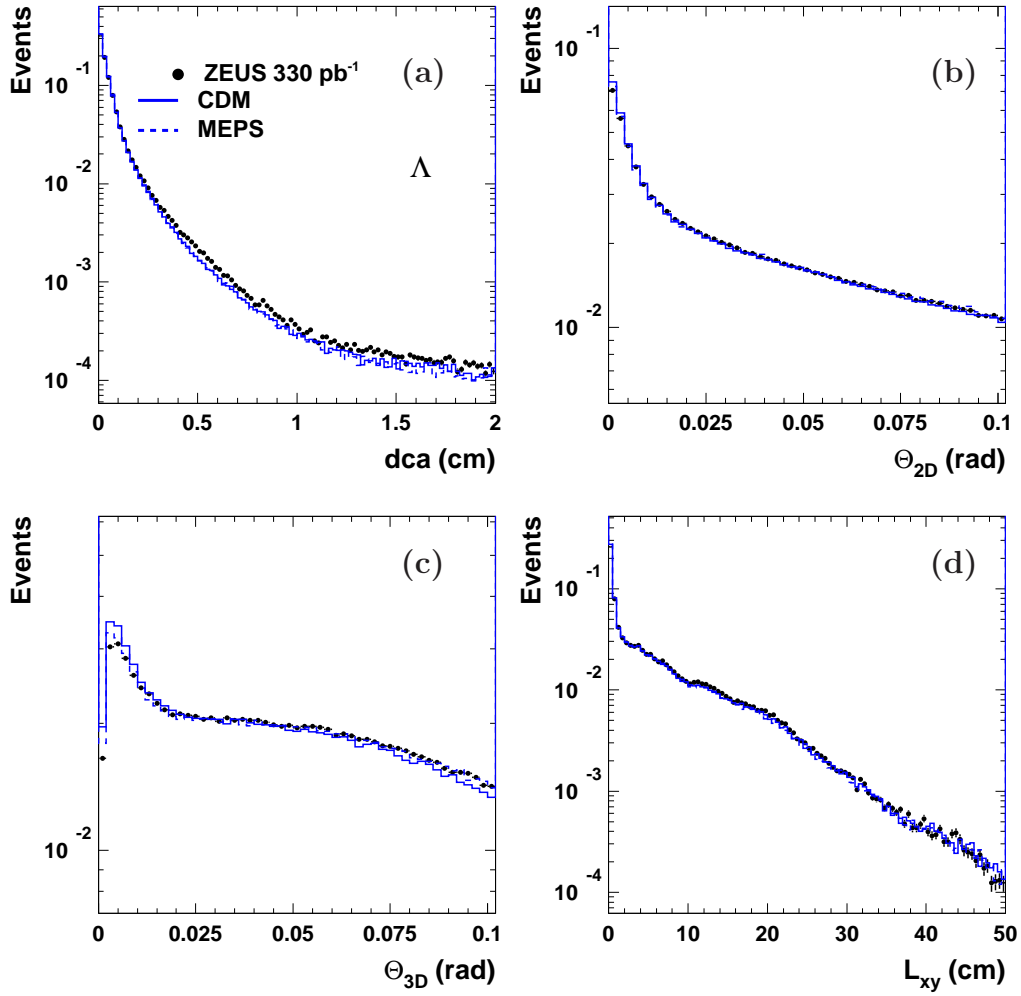
**Table 4:** The measured scaled momentum distributions  $(1/N)(n(\Lambda)/\Delta x_p)$  as functions of  $x_p$  in different regions of  $Q^2$ . Other details as in the caption to Table. 1.

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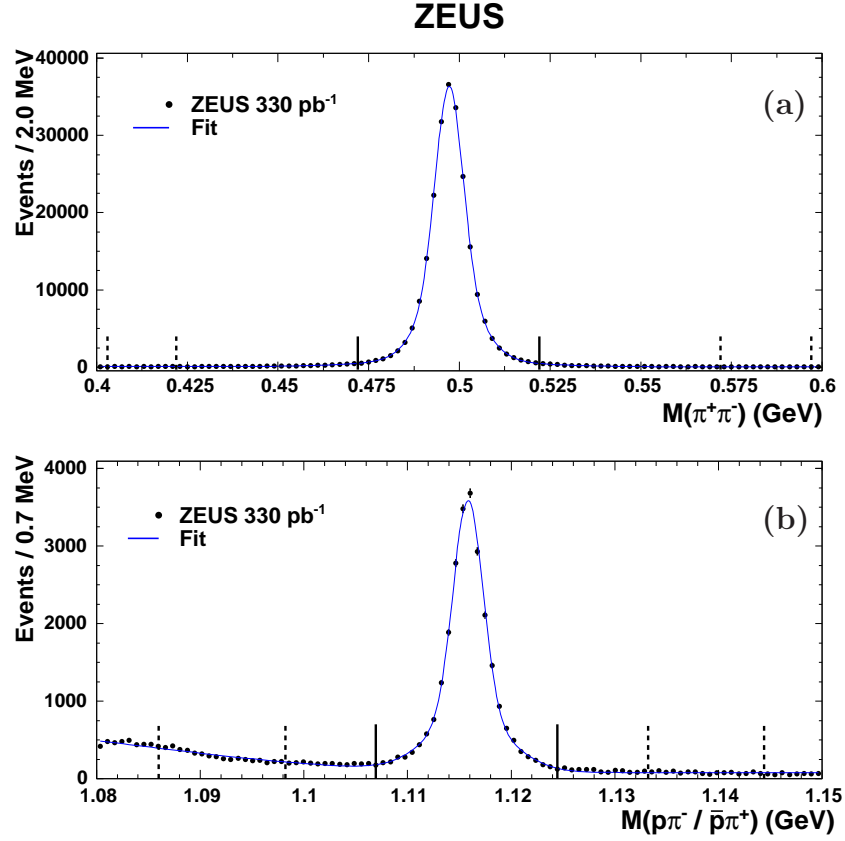


**Figure 1:** The normalised (a)  $dca$ , (b)  $\theta_{2D}$ , (c)  $\theta_{3D}$  and (d)  $L_{XY}$  distributions for data (dots) and Monte Carlo (histograms) for  $K_S^0$  candidates.

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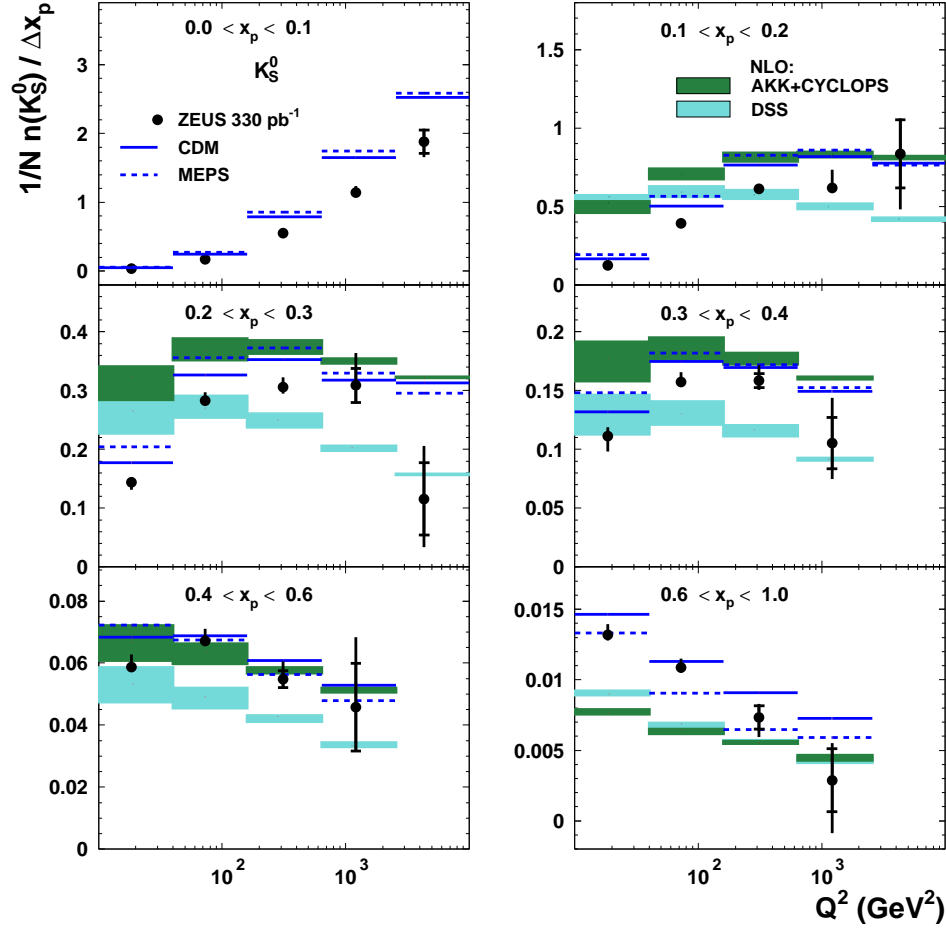


**Figure 2:** The normalised (a)  $dca$ , (b)  $\theta_{2D}$ , (c)  $\theta_{3D}$  and (d)  $L_{XY}$  distributions for data (dots) and Monte Carlo (histograms) for  $\Lambda$  candidates.

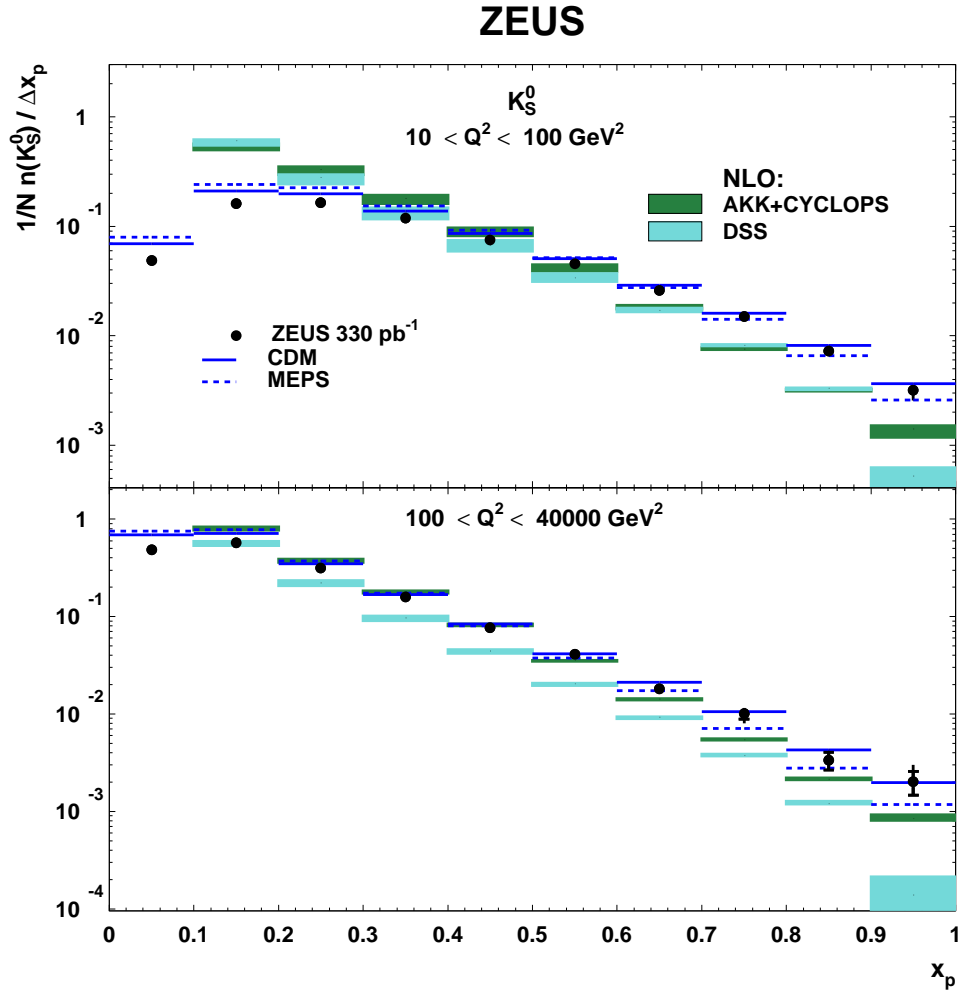


**Figure 3:** (a) The  $\pi^+\pi^-$  invariant-mass distribution for  $K_S^0$  candidates (dots). (b) The  $p\pi^-/\bar{p}\pi^+$  invariant-mass distribution for  $\Lambda/\bar{\Lambda}$  candidates (dots). In both (a) and (b), the solid line represents an indicative fit by two Gaussians and a (a) linear and (b) quadratic background function. The solid vertical lines indicate the signal window used in the analysis. The dashed lines indicate the two sideband regions used for the background subtraction in each kinematic bin.

## ZEUS

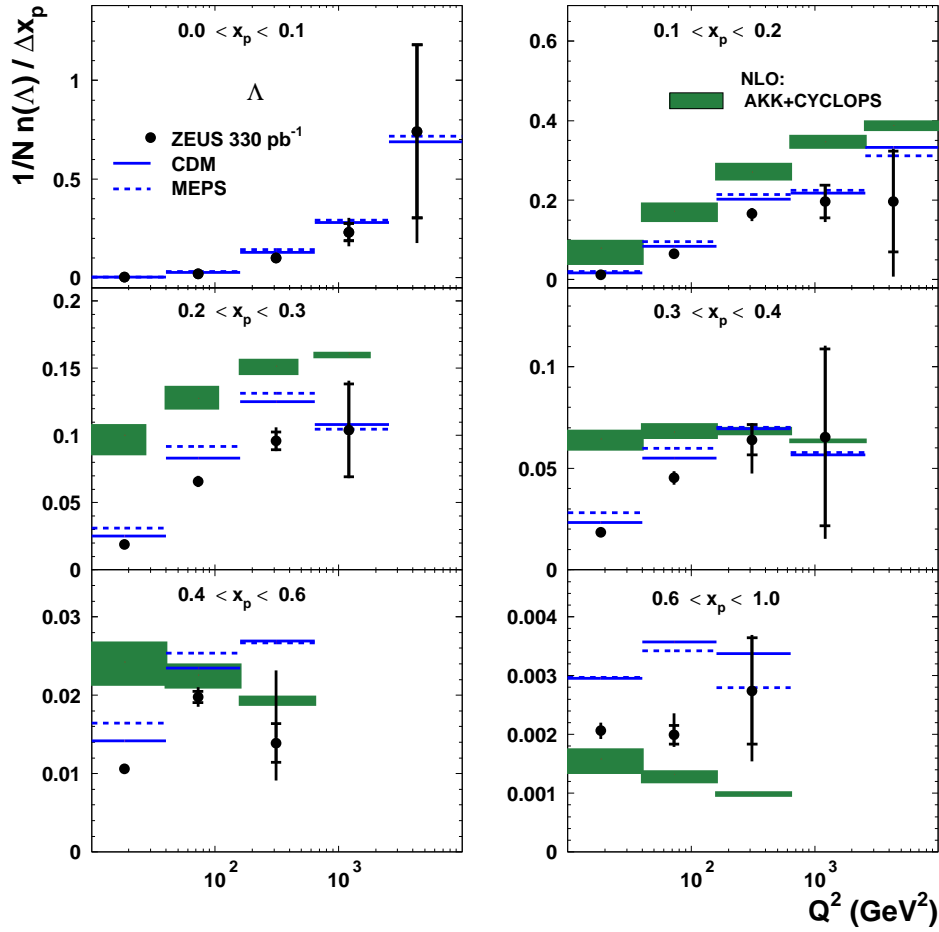


**Figure 4:** The measured scaled momentum distributions  $(1/N)(n(K_S^0)/\Delta x_p)$  as functions of  $Q^2$  in different regions of  $x_p$  (dots). The inner error bars represent the statistical uncertainty. The outer error bars show the statistical and systematic uncertainties added in quadrature. In some bins, the error bars on the data points are smaller than the marker size and are therefore not visible. For comparison, the NLO predictions of AKK+CYCLOPS (dark-shaded band) and DSS (light-shaded band) are also presented. The bands represent the theoretical uncertainty. The predictions from CDM (solid lines) and MEPS (dashed lines) are also shown.



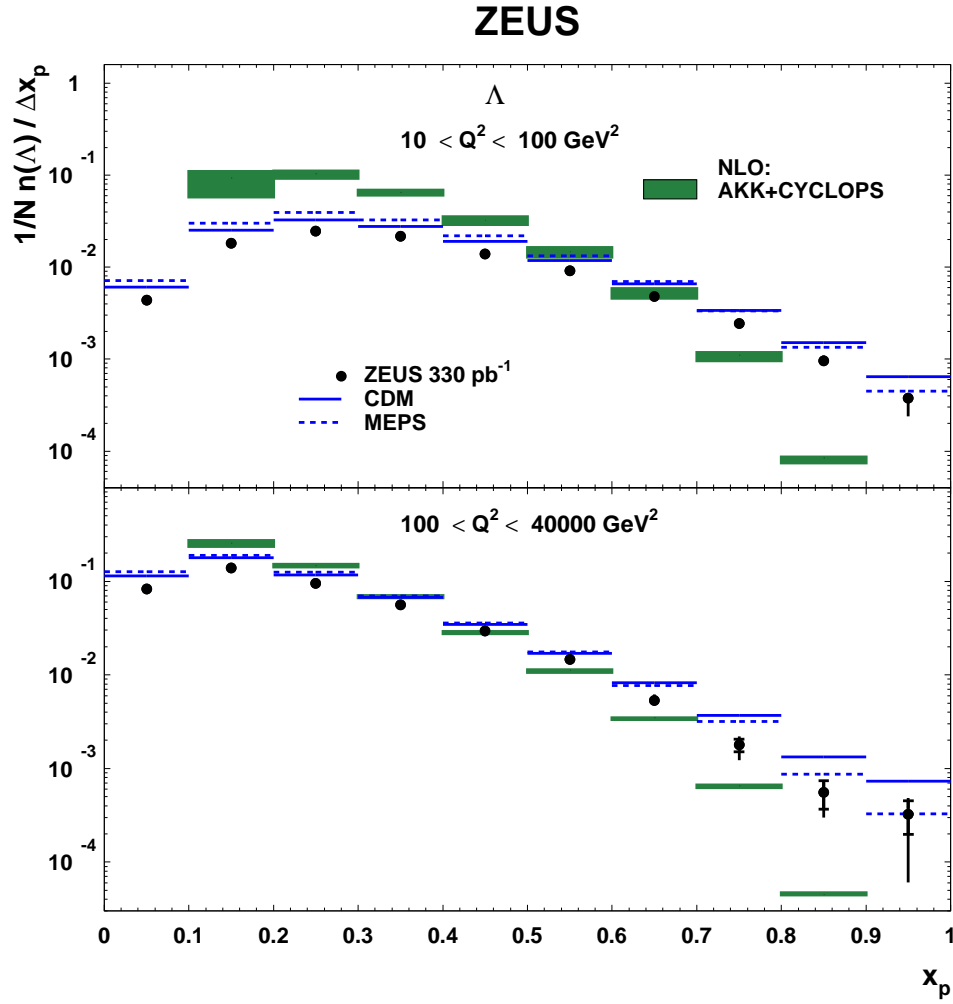
**Figure 5:** The measured scaled momentum distributions  $(1/N)(n(K_S^0)/\Delta x_p)$  as functions of  $x_p$  in different regions of  $Q^2$  (dots). Other details as in the caption to Fig. 4.

## ZEUS

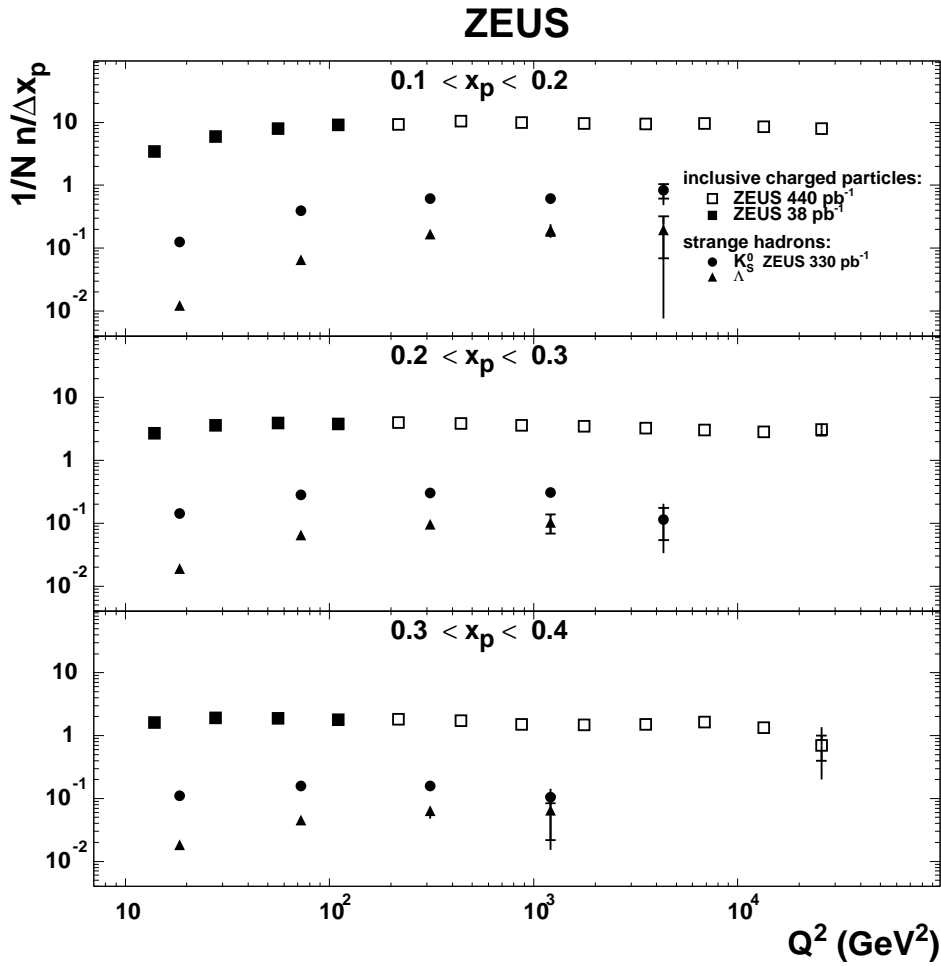


**Figure 6:** The measured scaled momentum distributions  $(1/N)(n(\Lambda)/\Delta x_p)$  as functions of  $Q^2$  in different regions of  $x_p$  (dots). Other details as in the caption to Fig. 4.





**Figure 7:** The measured scaled momentum distributions  $(1/N)(n(\Lambda)/\Delta x_p)$  as functions of  $x_p$  in different regions of  $Q^2$  (dots). Other details as in the caption to Fig. 4.



**Figure 8:** The measured scaled momentum distributions  $(1/N)(n(H)/\Delta x_p)$  for  $H = K_S^0$  (dots),  $\Lambda$  (triangles) and light charged particles (squares) as functions of  $Q^2$  in different regions of  $x_p$ . Other details as in the caption to Fig. 4.